Sablefish recruitment linked to anti-cyclonic eddies in the Gulf of Alaska

A.W. Smith[1], E. Di Lorenzo[1], M. M. Stachura[2], and S. K. Shotwell[3]

Sablefish reproductive success and the origin of mesoscale anticyclonic eddies in the Gulf of Alaska (GOA) were explored with a combination of recruitment data from a NOAA catch-at-age model, satellite data and ROMS ocean model. In the GOA, eddy formation follows large down-welling events and may induce mixing of nutrients and ocean column properties into the near-shore region inhabited by sablefish juveniles.
Satellite and ROMS ocean model data well captured the evolution of the eddies and showed strong correlation between SSH down-welling anomalies (SSHa) and recruitment. We also make use of tide gage data at fixed coastal locations near eddy formation sites. Using an ensemble Montecarlo approach, 3,000 cross-correlations of both ROMS SSHa and tide gage SSH with recruitment were conducted, with significant correlations of 0.45 and 0.60 observed. Using model simulations together with physical data allows us to forecast sablefish recruitment variability with 2-year lead.

[1] Department of Earth & Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA
[2] School of Aquatic and Fishery Sciences, University of Washington, Seattle, Washington, USA
[3] Auke Bay Laboratories/Ted Stevens Marine Research Institute, AFSC, NOAA, Juneau, Alaska, USA

Introduction

In the northern Pacific Ocean, the Gulf of Alaska (GOA) is home to a large variety of commercially and ecologically important long-lived groundfish stocks which help support the marine fishing industry prevalent in the state. Among these fish species, *Anoplopoma fimbria*, the sablefish (or black cod), is a highly valuable deep-water species with large movement rates and an early life history that begins offshore on the Alaskan continental slope. Environmental forcing is thought to be critical to determining recruitment, or the number of individuals surviving to enter the fishable adult population, of sablefish (Shotwell et al. *In Press*). In this study we explore the influence of mesoscale anticyclonic eddies in the GOA, and their relationship to sablefish survival.

Adult sablefish are typically encountered in deep water (200-1000m) along the continental slope, shelf gullies, and fjords (Wolotira et al. 1993). Spawning and egg incubation take place at depth (> 300 m). Upon hatch, larvae begin to feed immediately swimming to the surface (Mason et al. 1983) where they have been sampled far offshore up to approximately 250 km along the continental slope (Moser et al. 1994, Wing 1997). From spring spawning and hatch along the continental slope until winter settlement in near-shore waters, young-of-the-year (YOY) sablefish are obligate surface (neustonic) dwellers with extremely fast growth rates and high consumption demands (Kendall A.W. and A.C. Matarese, 1987; Sigler et al. 2001). During this time, YOY sablefish feed on primary consumers (e.g. copepods and euphausiids) (Yang, M.S. and M.W. Nelson, 2000); therefore, sablefish growth may be directly related to the presence of high productivity along their route towards the coastal waters in the GOA (Shotwell et al. *In Press*) (Fig. 1). Furthermore, laboratory studies on juvenile sablefish suggest some thermal intolerance to very cold water (Sogard, S.M. and B.L. Olla, 1998) and recent analysis of late larvae and juvenile sablefish otoliths from survey samples showed rapid growth rates which increased with warmer water temperatures (Sogard, S.M. 2011). This suggests that sablefish may be additionally sensitive to environmental forcing from changes in temperature.

In the surface ocean layer, larvae and juveniles follow euphausiids and other drifting algavores eastward through the GOA from late spring through late fall (Shotwell et al. *In Press*). During this time, sablefish encounter strong coastal anomalies in the mean flow of the Alaska Current (Rovegno, P.S., C.A. Edwards and K.W. Bruland, 2009) associated with the generation and propagation of ocean anti-cyclonic eddies. These large-scale eddies, which are evident in the satellite imagery as positive sea surface height anomaly (SSHa), are recurring features in the eastern GOA that form in the vicinity of three specific coastal sites (Yakutat, Sitka and Haida) (Ladd et al. 2007) (Fig. 2). As these eddies propagate into the offshore waters they entrain nutrients, especially iron, chlorophyll-A and zooplankton from the coast, which may enhance feeding conditions for the growth of fish larvae (Rovegno, P.S., C.A. Edwards and K.W. Bruland, 2009; Atwood 2010). These eddies may also transport larvae to favorable near-shore nursery habitats (Atwood et al., 2010). As juvenile sablefish migrate towards near-shore overwintering sites in the GOA, we hypothesize that the generation and strength of these semi-permanent eddies impact the recruitment of sablefish.

Using satellite observations from 1992-2011 and results from a historical hindcast from 1950-present of a high-resolution ocean model we explore the joint statistics of ocean eddies and sablefish in the GOA. Specifically, we explore the hypothesis that the generation and propagation of large eddies during strong downwelling events in the coastal GOA impacts the recruitment of sablefish.

Methods and data

Population data for sablefish is available from a large variety of fishery dependent and independent sources. This information is integrated within a statistical catch-at-age model to generate population estimates such as spawning biomass and recruitment that are presented in the annual stock assessment fishery evaluation (SAFE) report conducted by the National Oceanographic and Atmospheric Administration’s National Marine Fisheries Service (NOAA NMFS) (Hanselman et al., 2012). Within the model, recruits are estimated as two-year olds because traditional adult surveys do not select for these ages. Additionally, sablefish recruitment is not modeled using a traditional stock-recruitment relationship, rather it is computed as mean recruitment with annual recruitment deviations (Hanselman et al. 2012). This is because recruitments are extremely episodic, highly variable, and do not appear to be closely related to the level of spawning biomass (Shotwell et al. *In Press*). For this study we used the most recently available time series of recruitment estimates from the Alaska sablefish stock assessment (Hanselman et al., 2012). These estimates were then lagged by two years so that the estimate corresponded to the year at age-0 when sablefish are hypothesized to be most susceptible to the influences of mesoscale eddies.

Eddy strength and size are derived from both AVISO satellite observations (http://www.aviso.oceanobs.com/duacs) and existing high-resolution historical simulation with the Regional Ocean Modeling System (ROMS) for the Northeast Pacific (http://data.eas.gatech.edu/nepd.php, RUN: NCEP/NOAA (10km) 1950-2007). AVISO's Developing Use of Altimetry for Climate Studies (DUACS) system, a reanalysis assimilator which processes data from the Jason-1, ENVISAT and other AVISO satellite missions (G. Dibarboure et al. 2006), provided sea surface height anomaly data for the Northeast Pacific for 1992-2011 (SSALTO/DUACS)[2]. The Northeast Pacific ROMS hindcast used in this study was shown to capture the observed long-term changes in temperature, salinity and nutrients along Line P and is described in detail by Di Lorenzo et al. (2008; 2009). This model has also been used to understand eddy dynamics in the GOA (Combes and Di Lorenzo, 2007; Combes et al., 2009) including the generation of eddies in the eastern basin as a response to downwelling events (Combes and Di Lorenzo, 2007). We also make use of tidal gage data from Permanent Service for Mean Sea Level (PSMSL, http://www.psmsl.org/data) to check the model's ability to capture downwelling events prior to the satellite data. With strong autocorrelation between the model and recruitment time series, we use a Montecarlo approach to determine the significance of correlation between the two data sources. Sampling 3000 possible cross-correlations between two red-noise time-series with similar autocorrelation to the ROMS and recruitment data, we quantify significance of the correlation with a numerical probability distribution function (PDF) of the cross-correlations.

Anti-cyclone eddies and sablefish recruitment

Previous studies of eddy dynamics in the Gulf of Alaska show that the relaxation of the coastal circulation following strong downwelling events energizes large anticyclone eddies along the coastal Gulf of Alaska (Combes and Di Lorenzo, 2007). These events are associated with intensification of the Aleutian Low sea level pressure pattern, which often occurs during El Niño events (Alexander, 1992).

[2] The altimeter products were produced by SSALTO/DUACS and distributed by AVISO, with support from CNES

For example, following the 1997 El Niño, a strong downwelling event and eddy formation was reported along the eastern side of the GOA (Melsom et al. 1999; Meyers et al. 1999). This event is clearly visible in satellite imagery as strong positive anomalies along the coastal GOA during the period Jan 1998 to Aug 1998 (Fig. 2). These types of events are also relatively well reproduced in the ocean model simulations with the ROMS (Fig. 3). The signature of the fully developed Haida and Sitka eddies in the ROMS are consistent with the satellite observations (e.g. during April, Fig. 3). In both the satellite and the ROMS model we find that these eddies have residence times of many months including generation and propagation in the GOA.

To explore the relationship between the downwelling events, eddy formation and sablefish recruitment we analyzed the joint statistics between the SSHa and the recruitment time series. Given the short temporal coverage of the satellite SSHa data (e.g. 1992-2011) we use the ROMS SSHa (e.g. 1950-2007) to compute lead/lag correlation maps between the recruitment time series and SSHa during the winter period when eddies are energized in the GOA (Figure 4). The correlation maps (Fig. 4) show that the recruitment time series tracks a typical evolution of a strong downwelling event (Fig. 4A, B) and subsequent formation of strong eddies like the Yakutat, Sitka and Haida (see Fig. 4 C, D). This progression is consistent with the strong downwelling events found on the 1998 satellite and model composites (Fig. 2 and 3). To develop a ROMS SSHa index that tracks strong winter downwelling and eddy generation events we calculated the average ROMS SSHa at three locations along the coastal GOA where the downwelling events anomalies are strong (Fig. 4B). These locations are also selected based on the availability of coastal tide gauge data that we use to test the accuracy of the model in capturing the observed history of the coastal circulation (Fig. 4E, the ROMS SSHa index is significantly correlated with the tide gauges R=0.6). A direct comparison of the ROMS SSHa index with the sablefish recruitment time-series reveals significant temporal correlations (R=0.45, Fig. 4F). These results provides empirical support to the hypothesis that the generation and propagation of large eddies during strong downwelling events in the coastal GOA impacts the recruitment of sablefish, and that empirical indices of eddy activity (e.g. the ROMS SSHa index) may be exploited to hindcast historic estimates of sablefish recruitment and better understand how future oceanographic changes, including eddies, may impact the sablefish population.

Discussion and hypothesis

Unlike observations available for mesoscale ocean perturbations like eddies from satellite data, biomass and recruitment estimates for groundfish species such as sablefish require time- and resource-intensive surveying at-sea. Furthermore, few surveys have been conducted to sample the early life history stages of sablefish (e.g. Wing 1997), which limits our current understanding of the ecosystem dynamics and environmental forces acting on this species. Although this lack of field observations prevents us from fully understanding the process that links physical eddy dynamics and sablefish recruitment, the historical simulations of the ROMS model in the GOA provide statistical support to the hypothesis that changes in eddy-scale circulation impact the recruitment of sablefish. An index of the GOA eddy-scale circulation shows that sablefish recruitment is higher in years characterized by strong downwelling and eddy generation events (see discussion of Fig. 4). These events are well captured in the ROMS model as evident from the comparison of the 1997-1998 El Niño event between satellite and model (Fig. 2, Fig. 3), and from the comparisons of the ROMS SSHa with tide gauges data at the generation sites of the Sitka, Yakutat and Cordova eddies (Fig. 4).

While significance in relationships cannot explain all factors associated with the biological component of this study, using model simulations in tandem with physical data (i.e. tide gage SL heights) allows us to forecast the variability in sablefish with a 2-year lead. This approach may be developed into a valuable asset to aid the stock assessment model and subsequent resource allocation and may be extended to other commercially viable species. Further studies and observations are required to explore the mechanisms by which changes in regional scale circulation impact fish species in the GOA.

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Figure captions

Figure **1.** Sablefish's highly motile early life history (ELH); Populations of juveniles susceptible to propagating physical forcings like eddies.

Figure **2**. AVISO SSHa showing Sitka and Haida eddies in GOA (48 - 61N ; 127.5 - 153 W) from January - August 1998.

Figure **3.** ROMS SSHa showing Sitka and Haida eddies in GOA (48 - 61**N** ; 127.5 - 153 **W**) from January - August 1998

Figure **4.** (A,B,C,D) Spatial correlation maps between the sablefish recruitment annual timeseries and ROMS SSHa for the month Oct-Jan. (E) Correlation of monthly ROMS model SSHa index with the equivalent index computed using de-trended tide gage data at Sitka, Yakutat and Cordova region (see black circle in panel A). (F) Correlation of November ROMS model SSHa index (defined as the average SSHa in blue circles shown in panel B) with sablefish recruitment annual data.